Renewable and Sustainable Energy Reviews 14 (2010) 2946–2955

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Bio-fuels for the gas turbine: A review

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ARTICLE INFO

Article history:
Received 24 May 2010
Accepted 15 July 2010

Keywords:
Gas turbine
Bio-fuel
Alternative fuels
Emission
Bio-diesel
Biomass
Syngas

ABSTRACT

Due to depletion of fossil fuel, bio-fuels have generated a significant interest as an alternative fuel for the future. The use of bio-fuels to fuel gas turbine seems a viable solution for the problems of decreasing fossil-fuel reserves and environmental concerns. Bio-fuels are alternative fuels, made from renewable sources and having environmental benefit. In recent years, the desire for energy independence, foreseen depletion of nonrenewable fuel resources, fluctuating petroleum fuel costs, the necessity of stimulating agriculture based economy, and the reality of climate change have created an interest in the development of bio-fuels. The application of bio-fuels in automobiles and heating applications is increasing day by day. Therefore the use of these fuels in gas turbines would extend this application to aviation field. The impact of costly petroleum-based aviation fuel on the environment is harmful. So the development of alternative fuels in aviation is important and useful.

The use of liquid and gaseous fuels from biomass will help to fulfill the Kyoto targets concerning global warming emissions. In addition, to reduce exhaust emission waste gases and syngas, etc., could be used as a potential gas turbine fuel. The term bio-fuel is referred to alternative fuel which is produced from biomass. Such fuels include bio-diesel, bio-ethanol, bio-methanol, pyrolysis oil, biogas, synthetic gas (dimethyl ether), hydrogen, etc. The bio-ethanol and bio-methanol are petrol additive/substitute. Bio-diesel is an environment friendly alternative liquid fuel for the diesel/aviation fuel.

The gas turbine develops steady flame during its combustion; this feature gives a flexibility to use alternative fuels. Therefore so the use of different bio-fuels in gas turbine has been investigated by a good number of researchers. The suitability and modifications in the existing systems are also recommended.

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1. Introduction

World energy consumption has increased 17-fold in the last century and emissions of CO_2, CO, SO_2 and NO_x from fossil-fuel

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.07.025

combustion are the main causes of atmospheric pollution. Worldwide petroleum reserves are expected to be depleted in less than 50 years at the present rate of consumption. In this scenario, bio-fuels have emerged as alternative sources of energy and offering many other benefits including sustainability, reduction of greenhouse gas emissions, rural development and security of supply [1].

At present bio-energy use covers 9–14% of the global demand, most of which as traditional, low tech and inefficient using in cooking and heating in developing countries. Different global energy scenario studies indicate that in India biomass may contribute much more: up to 30% of the energy supply by 2100 [2]. Bio-fuels produced from biomass such as plants or organic waste could help to reduce dependence on oil and GHG production. These bio-fuels have the potential to reduce CO_2 emission because the plants they are made from use CO_2 as they grow [3,4].

The gas turbine is a continuous-flow engine which develops steady flame during its combustion. This favorable feature allows the use of various fuels and also provides clean combustion in the gas turbine. Moderate compression ratios, robust mechanical designs and versatile combustion systems helps to utilize a wide series of bio-fuels such as alcohols, bio-diesel, LCV gasified biomass, synthetic gas, hydrogen, etc., in addition to conventional natural gas. These fuel properties influence on gas turbine efficiency, NO_x emission and combustion design [5]. The clean combustion of biomass-derived biogas (LHV < 25% of natural gas) and hydrogen enriched fuels is due to lean, premixed combustion, resulting low-NO_x emissions [6].

The gas turbine engine has number of attractive features such as compact size, short delivery, high flexibility, reliability, fast starting, fast loading, lower manpower operating needs and better environmental performance, as compared to steam turbine plant. However, it suffers from low efficiency, especially at part load. This shortcoming of gas turbine is overcome by using cogeneration, which is a simultaneous production of power and thermal energy with the use of energy of the exhaust gases [7]. The combined cycle technology is now well established and superior to any of the competing gas turbine based systems. Mixed air steam turbines (MAST) are among the possible ways to improve the performance of gas turbine based power plants. Water or steam injection in to the combustion chamber for NO_x emissions control is also commonly used. Depending on the amount of water or steam injection needed to achieve the desired NO_x level, output will also increase because of the additional mass flow [8].

Gas turbine driven cogeneration plants using bio-fuels can be located close to energy consumption centres, especially for remote areas of developing countries where grid power is not available. They can produce their own fuel such as biomass-derived fuels. Gas turbines are having large power range, and they are suited with certain modifications in fuel supply systems. Current gas turbine systems though, are capable of burning such fuels, are normally developed for a single specific fuel (such as natural gas or diesel fuel). In these remote areas, different types of vegetable oils are grown/produced locally but it may not be possible to chemically process them due to logistics problems in rural settings. Hence using heated or blended vegetable oils as petroleum fuel substitutes/additives is also an attractive option [9].

Sunflower and rapeseed oil are the generally used raw material for the production of bio-diesel in Europe whereas Soybean is used in USA. Thailand uses palm oil, Ireland uses frying oil and animal fats. In India it is proposed to use non-edible oil for producing bio-diesel. Presently many species are being grown which yield seed containing non-edible oils. The present production is being used and much surplus is not available. It is required to initiate a major plantation program of different oil born plants to provide the oil needed. This plantation can be easily under taken in the farmers' fields and their boundaries, deserted lands, public lands along railway tracks, highways, canals and community and government lands in villages, Its plantation, seed collection, oil extraction, etc., will create employment opportunities for a large number of people, particularly the tribal and the poor, and it will help to rehabilitate unproductive and wastelands and save precious foreign exchange by substituting imported crude.

The fibrous, grassy materials, agricultural residues, municipal wastes and industrial wastes are also the feed stocks for the production of the synthetic fuels such as bio-methanol, bio-ethanol, DME (dimethyl ether), SNG (synthetic natural gas) and hydrogen via gasification and synthesis. Production of biogas can be produced either from organic wastes or recovered from municipal solid waste landfills. The recovery of biogas is important not only as a resource, but also for avoiding the discharge of greenhouse gas in the atmosphere. Upgraded biogas compressed at a pressure around 200 atm and filled in gas cylinders can also be used as a transport fuel [10].

Compatibility of different bio-fuels with turbine fuel delivery systems is primarily a function of fuel viscosity and, in the case of ethanol, it is material corrosion. In low temperature areas bio-diesel can also be preheated as diesel oil. The max allowable range of dynamic viscosity in the gas turbine is about 12 cSt with modifications in its fuel nozzle. All of the fuels except pyrolysis oil fall within this range. However, blending of pyrolysis oil with ethanol would reduce the viscosity of mixture to the desired range. Blending of the other fuels with diesel fuel also has a favorable effect on both viscosity and cost [11]. Now finally selection of the liquid and gaseous fuels will be based upon the atomization and spray characteristics of liquid fuels, the combustion and emission characteristics of the selected alternative fuel, flames, the sooting tendency and NO_x emission properties of the fuels under various operation conditions. The adaptability of existing conventionally fuelled combustors for use with the selected alternative fuels will depend on these parameters. The selection may based on availability, composition, physical properties, and costs of the fuel [6].

2. Straight vegetable oils

Pure vegetable oil cannot be used directly in gas turbine [1]. So, they have to be modified to bring their combustion related properties closer to those of diesel. Such a fuel modification is mainly aimed to reduce the viscosity to eliminate flow/atomization related problems. Four techniques can be used to reduce the viscosity of vegetable oils; namely heating, dilution/blending, micro-emulsion, and trans-esterification [9].

Vegetable oils mainly contain triglycerides (90–98%) and small amounts of mono- and di-glycerides. Triglycerides contain three fatty acid molecules and a glycerol molecule. They contain significant amounts of oxygen. The fatty acids vary in their carbon chain length and number of double bonds present in their molecular structure. Vegetable oils contain free fatty acids (generally 1–5%), phospholipids, phosphatides, carotenes, tocopherols, sulfur compounds and traces of water. Commonly found fatty acids in vegetable oils are stearic, palmitic, oleic, linoleic and linolenic acid [9].

The problems attributed to high viscosity and poor volatility of straight vegetable oils is due to large molecular weight and bulky molecular structure. High viscosity of vegetable oils (30–200 cSt at a temperature of 40 °C) as compared to mineral diesel (2 cSt at the same temperature) lead to unsuitable pumping and fuel spray characteristics. Larger size fuel droplets are injected from injector nozzle instead of a spray of fine droplets leads to inadequate air-fuel mixing, poor atomization, lower volatility, and inefficient

mixing of fuel with air contribute to incomplete combustion. This results an increment in higher particulate emissions, combustion chamber deposits and gum formations [9].

The viscosity of vegetable oils can be reduced by increasing its temperature (using waste heat of the exhaust gases) and thereby eliminating its effect on combustion and emission characteristics. Vegetable oils have energy density, cetane number, and heat of vaporization comparable with mineral diesel. In addition, they are biodegradable, non-toxic, and have a potential to significantly reduce pollution. Vegetable oils and their derivatives lead to substantial reductions in emissions of sulfur oxides, carbon monoxide (CO), poly aromatic hydrocarbons (PAH), smoke and particulate matter (PM). Moreover the effect of this emission is insignificant, since carbon dioxide (CO_2) emitted during combustion is recycled in the photosynthesis process in the plants. [9]

The fuel volatility and spray parameters of liquid fuel influences the combustion and emission characteristics in diffusion controlled gas turbine combustor. The combustion efficiency reduces drastically with a decrease in fuel volatilities at lower spray cone angle. There is also an influence of some important operating parameters like inlet swirl, air-fuel ratio, inlet pressure and temperature on flow and combustion characteristics in the combustor using both gaseous and liquid fuels [12]. Lefebvre stated that the combustion efficiency should increase with finer initial droplets, as it increases the evaporation rate of the fuel [13].

Trans-esterification is well accepted and best suited method without significant long-term operational and durability issues. However, this increases the cost of processing because of the trans-esterification reaction involving chemical and process heat inputs [14].

3. Bio-diesel

Bio-diesel is an environmental friendly fuel that can be used in any gas turbine without modification. Bio-diesel is better than diesel fuel in terms of sulfur content, flash point, aromatic content and biodegradability. There has been renewed interest in the use of vegetable oils for making bio-diesel due to its less polluting and renewable nature as against the conventional petroleum diesel fuel. Due to its environmental benefits, the share of bio-diesel in the automotive fuel market is growing fast [1].

India's demand for diesel is almost six times that of gasoline hence finding alternative to mineral diesel is important. Diesel is largely utilized in the transport, agriculture, commercial, domestic, and industrial sectors for the generation of power/mechanical energy, and the substitution of even a small fraction of total consumption by alternative fuels will have a significant impact on the economy and the environment. Out of the alternative fuels, bio-diesel obtained from vegetable oils holds good promises as an eco-friendly alternative to diesel fuel [15]. Bio-diesel is fatty acid ethyl or methyl ester made from virgin or used vegetable oils (both edible and non-edible). The main commodity sources for bio-diesel in India can be non-edible oils obtained from plant species which bear seeds rich in oil such as Jatropha Curcas (Ratanjyot), Pongamia Pinnata (Karanj), etc.

It is derived from vegetable oils by modifying their molecular structure through a trans-esterification process. Trans-esterification involves a reaction in a triglyceride and alcohol in presence of a catalyst to produce glycerol and ester. Yield of bio-diesel is affected by molar ratio, moisture and water content, reaction temperature, stirring, specific gravity, etc. [16].

The characteristics of bio-diesel are close to diesel fuels, and therefore bio-diesel becomes a strong alternative to replace the diesel fuels. The conversion of triglycerides into methyl or ethyl esters through the trans-esterification process reduces the molecular weight to one-third that of the triglyceride reduces the viscosity by a factor of about eight and increases the volatility marginally. Bio-diesel has viscosity close to diesel fuels. These esters contain 10–11% oxygen by weight, which may encourage more combustion than hydrocarbon-based diesel fuels. Bio-diesel has lower volumetric heating values (about 12%) than diesel fuels but has a high cetane number and flash point. The high flash point attributes to its lower volatility characteristics [17].

This diesel substitute requires very little or no gas turbine modifications up to 20% blend and minor modification for higher percentage blends. It can be blended at any level with petroleum diesel to create a bio-diesel blend or can be used in its pure form. It can be stored just like the diesel and hence does not require separate infrastructure. The use of bio-diesel in gas turbine results in substantial reduction of un-burnt hydrocarbons (UHC), carbon monoxide and particulate matters without reducing the output power significantly [18]. The reduction in emissions by using 20% blend of bio-diesel in diesel fuel was about 12% for CO and particulate matter (PM) emission and 20% for UHC emissions. The reduction in emissions by using 100% bio-diesel was about 48% for CO and PM and 68% for UHC for the gas turbine. However, there is a marginal increase in NO_x (1–6%) [17]. Uncontrolled emissions like poly aromatic hydrocarbons (PAH), etc., were also found to be less. Bio-diesel is considered clean fuel since it has almost no sulfur content (typically it is less than 15 ppm), no aromatics and has about 10% built-in oxygen, which helps it to burn fully. Bio-diesel also has superior lubricity. It can also be used as a lubricating agent for conventional diesel, so the diesel can be free from sulfur.

Flash point of bio-diesel is high (>100 °C). Its blending with diesel fuel can be utilized to increase the flash point of diesel particularly in India where flash point is 44 °C well below the world average of 55 °C. This is important from the safety point of view. Cetane number (CN) of the bio-diesel is in the range of 48–60, this higher cetane number improves the ignition quality even when blended in the petroleum diesel. The viscosity of bio-diesel is higher (1.9–6.0 cSt) and is reported to result into gum formation on injector. However, blends of up to 20% do not give any problem. While a gas turbine can be run by 100% bio-diesel use, the existing gas turbines can use 20% bio-diesel blend without any modification [1].

The presence of oxygen in bio-fuel molecules was expected to result in leaner combustion, and hence increase in the thermal efficiency. Higher thermal efficiencies with pure bio-diesel may be attributed to lower equivalence ratios (leaner fuel/air mixtures) and more complete combustion due to the presence of extra oxygen in the bio-diesel. Furthermore, the operation of the turbine with the products of a leaner mixture approaches to the air-standard cycle. The addition of bio-diesel such as soya methyl ester, canola methyl ester, and recycled rapeseed methyl ester in JET-A fuel for gas turbine have reduced the static thrust and specific fuel consumption, and increased thermal efficiency [19].

The turbine inlet temperature and exhaust gas temperature for all fuels do not show significant changes with the fuel type. CO and NO emission decrease when bio-diesel was used. The bio-diesel–JET-A blends appear promising, while emitting the least amount of pollutant with no significant reduction in static thrust [19].

The turbine speed is a function of turbine inlet temperature (TIT). As the speed increased, the turbine inlet temperature increases due to increase of the heat release/heat loss ratio from the combustor. The temperature following combustion of pure bio-diesel was slightly lower than that of JET-A at low speeds and approached that of JET-A at high speeds. The exhaust gas temperature (EGT) is almost same for all fuels [19].

Micro-turbines are the subset of combustion gas turbines being used and improved for stationary power generation. Micro-turbines have evolved from the efforts to make gas turbines smaller for automotive or aerospace applications. It tends to fall in

the range of 5–500 kW sizes. The bio-diesels and its blends used as fuel in micro-turbines led to no significant changes in the engine performance and behavior compared to diesel fuel [20].

The exhaust emissions were evaluated for pure soya bio-diesel and its blends and conventional diesel. There were no significant changes in the engine thermal performance even when compared to the use of soya bio-diesel with JET-A fuel [21]. During endurance tests in the turbine engine using rapeseed oil bio-diesel, the turbine nozzle and rotor presented a significant fouling deposit and damage. This turbine was also tested with automotive diesel/castor bio-diesel blends. Castor bio-diesel is the one that presents the highest viscosity. In order to avoid problems regarding the high viscosity of fuel, a preheating system was placed in the bio-diesel reservoir, to reduce its viscosity [18].

Due to preheating, bio-diesel created no problem related to atomization process in the tests, and the thermal efficiency of the turbine reaches the level of around 26%. The minimum heat rate obtained at full load was for the bio-diesel from palm oil, and the maximum was for castor oil [19]. In order to diminish the viscosity, it is necessary to heat the fuel previously, especially for bio-diesel concentrations higher than 50%. Such an attempt results in good performance, and no problems related to viscosity [22].

The combustion of bio-diesel derived from waste cooking oil (WCO) indicates that it requires less air for stoichiometric combustion due to the presence of oxygen in the fuel and such a bio-diesel stand as a potential alternative fuel for power generation application with the good efficiency at blended ratio of 20% bio-diesel and 80% distillate. This has shown the feasibility of using bio-diesel and its blends for gas turbine application. Bio-diesel was produced from waste cooking oil, mainly from palm oil sources. The oil burner was able to fire these blends of fuel without any modification or pretreatment [23].

To measure the fuel performance different factors like volatility, droplet formation and ease of ignition have been included and an acceleration test has been done. The engine acceleration using bio-diesel from used oil is about 15% less than that of bio-diesel made from unused oil [24].

During the thrust test of bio-diesel made from unused, used cooking oil and JET-A fuels, the thrust produced by bio-diesel fuel was proportionately less than the JET-A for all engine speeds. The thrust difference amounted to about 8% less. Ignition in the engine with either of the bio-diesels was not detectably different from that with the JET-A. A visual observation of the exhaust jet color and size indicated no difference. There was a difference in the odors of the exhausts. Exhaust gas temperature (EGT) is very similar with all these fuels [24].

Fuel properties affect the gas turbine performance such as injector operation, droplet sizes and fuel vaporization characteristics. The effect of bio-diesel's properties such as viscosity and volatility result in low atomization and longer evaporation times compared to diesel. Theoretical and experimental findings indicate that optimizing the fuel injection process will reduce NO_x emissions for bio-diesel. The minimum NO_x emission levels achieved for bio-diesel still exceed the minimum level attained for diesel. The atomization and some factors contribute to the higher NO_x emissions observed for bio-diesel. The use of lean, premixed, pre-vaporized combustion may be use to achieve low pollutant emissions. Improving atomization quality will result in a reduction of NO_x and CO emissions [25].

For the use of bio-diesel in commercial and military flights, few studies have been done. *Baylor Institute for Air Science* has tested blends of bio-diesel from waste cooking oil and plant and animal matter in JET-A (up to 30% by volume) in a modified gas turbine engine. It was found that nitric oxide (NO) concentration in the exhaust gases decreased with bio-diesel content. No difference in the performance or fuel consumption was found between pure JET-A and JET-A blended with up to 20% bio-fuel for the same power output. There is no significant reduction in efficiency with bio-diesel [19].

Palm oil methyl ester derived from palm oil is the most promising alternative to diesel because its property is similar to conventional diesel. The tendency of PME is to produce soot is less than diesel. NO_x emission level is a function of fuel atomizing pressure [26]. Several bio-oils and heavy oils tend to be very viscous and require preheating as well as external compressed air may be used for satisfactory atomization. The preheating itself has to be carried out in such a manner that the fuel does not go through harmful chemical change while in the fuel line. For this purpose the alternative fuel tank is equipped with a heater. Bio-oils tend to be acidic and require the entire handling system and the fuel lines to be fabricated from corrosion resistant materials. Particulate matter in the fuel needs to be filtered to prevent plugging of fuel nozzles and for satisfactory combustion. Bio-oil produces no SO_x emissions but NO_x and CO emissions need to be kept within allowable limit. These alternative fuels tend to produce deposits on hot section that can produce corrosion and may reduce efficiency significantly [27].

Fuel nozzle design is extremely important. The fuel nozzle in a dual fuel mode, allows start up on diesel and gradual switch over to alternative fuels. In addition, they allow for enhanced atomization with external compressed air supply. The duel fuel nozzle has three channels for the diesel fuel, for the alternative fuels and for the external compressed air to improve fuel atomization. External compressed air is the air taken from the gas turbine compressor. Cooling air supply holes were rearranged in size and location for better mixing with the combustion air in the front section of the combustor and to keep the combustors wall temperature in the allowable range below 800 °C [27].

4. Bio-ethanol

Ethanol is derived from alcoholic fermentation of sucrose or sugar cane and corn (60–70% starch). It is a well-established and well-known technology, generally used for human consumption in the form of beers, wines and spirits [28]. It is possible that wood, straw and even household wastes may be economically converted to bio-ethanol by hydrolysis process. Starches and cellulosic biomass usually require expensive pretreatment. Ethanol is the most widely used liquid bio-fuel [1].

Sugars are produced during steam explosion, dilute acid pre-hydrolysis process of carbohydrates like hemicelluloses and cellulose in plant materials. Fermentation is an anaerobic biological process in which sugars are converted to alcohol by the action of microorganisms, usually yeast. The resulting alcohol is ethanol. The chemical reactions are the enzymatic hydrolysis of sucrose followed by fermentation of sugar. Invertase enzyme in the yeast catalyzes the hydrolysis of sucrose to convert it into glucose and fructose. Zymase enzyme present in the yeast converts the glucose and the fructose into ethanol.

$$\underset{\text{Surcose}}{C_{12}H_{22}O_{11}} \rightarrow \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Fructose}}{C_6H_{12}O_6} \qquad C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The production process of ethanol from the corn (starch) includes conversion of starch in to D-glucose in the presence of gluco-amylase. Then it is followed by distillation and dehydration to yield anhydrous bio-ethanol.

Use of ethanol in the pure state or as a blend would probably require replacement of any white metal or aluminum in the system as well as some elastomers. The heat content of ethanol is higher than methanol. But it is still only 63% of diesel. Emissions from ethanol are about 48% of diesel; it is lowest of any of the fuels. Its clean burning characteristics extend turbine life, possibly by as

much as 100%. Its disadvantages are low vapor pressure leading to rapid evaporation and miscibility with water, both factors creates handling problems. It burns with an invisible flame, which may create a hazard outside the turbine [11].

5. Bio-methanol

Methanol is currently made from natural gas but can also be made using biomass via partial oxidation reactions. Biomass and coal can be considered as a potential fuel for gasification and syngas production followed by methanol synthesis [1]. Most processes require extra/additional oxygen for the intermediate conversion of the biomass into a synthesis gas ($H_2 + CO$). Syngas or biogas is reformed to methanol under high pressure and temperature in presence of catalyst [28].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad CO + 2H_2 \rightarrow CH_3OH$$

Methanol from coal may be a very important source of liquid fuel in the future. The coal is first pulverized and cleaned, then fed to a gasifier bed where it is reacted with oxygen and steam to produce the syngas. Methanol made using synthesis gas (syngas) with H_2 and CO in a 2:1 ratio. The syngas was transformed to methanol in a fixed catalyst bed reactor. Coal derived methanol has many preferable properties as free of sulfur and other impurities.

$$CO + 2H_2 \rightarrow CH_3OH$$

Methanol is poisonous and burns with an invisible flame. As the flash points of methanol and ethanol fuels (11 and 13 °C, respectively) are within normal range of ambient temperatures, it means that any fuel tank containing alcohol fuel will have a flammable atmosphere within it. This is in marked contrast to current hydrocarbon fuels. Therefore, the use of alcohol fuels as direct replacements to petrol or diesel introduces a significant hazard of an explosive mixture being present in the fuel tank [28].

6. Lean, premixed, pre-vaporization of liquid bio-fuels

By this technique the emission can be further reduced to meet the latest stringent emission norms. The redesign of fuel injector and a pre-vaporization premixing tube (PP tube) is required for evaporation of fuel spray. Evaporation of liquid fuel spray in the PP tube is assisted by higher swirled air produced by vane placed in the path of air. The swirl air assists atomization and distribution of the fuel. This gives good combustion for lean fuel–air mixture (equivalence ratio 0.2–0.5) and it reduces emission of NO_x and CO [29].

During lean, premixed, pre-vaporized (LPP) combustion, liquid bio-fuels, such as bio-diesel and ethanol are converted into a gas. This LPP gas can then be burned with low emissions and providing substantial fuel flexibility. This provides a clean and reliable use of liquid bio-fuels that can be a primary source for power generation or be a back-up source for inconsistent renewable energy sources such as wind and solar [30].

Micro-gas turbine utilizing the lean, premixed, pre-vaporized combustion. Due to low pressure and low combustor inlet temperature, the liquid fuel is evaporated on a hot surface since compressor air temperature is too low for an intense evaporation of a fuel droplet spray. The liquid fuel film on the inner surface of the tube is evaporated by heat transfer from the hot combustion gases through the tube wall. Lean burning conditions and a homogeneous fuel–air mixture lead to low flame temperatures and hence to reduced nitrogen oxide (NO_x) formation [31].

7. Biogas

Anaerobic digestion of bio-wastes occurs in the absence of air, the resulting gas is called biogas. It is a mixture consisting mainly of CH_4 and CO_2. Biogas is a valuable fuel which is produced in digesters filled with the feedstock like dung or sewage solid wastes.

8. Syngas derived from biomass

Biomass is a mixture of its structural constituents. Biomass gasification has attracted the highest interest among the thermo-chemical technologies as these offer higher efficiencies in relation to combustion, Biomass gasification can take place at higher temperatures and produces a mixture of gases with H_2. The synthesis gas includes mainly H_2 and carbon monoxide (CO), which is also called syngas. Biomass can be converted to bio-syngas by non-catalytic, catalytic and steam gasification processes. The composition of bio-syngas from biomass gasification is as follows [1]:

CO: 22–36%,
H_2: 22–32%,
CO_2: 21–30% and
CH_4: 8–11%.

Biomass, a renewable source, is well recognized as a potential fuel for the future. In India alone, the likely usable power potential for biomass could be as much as 61×10^9 kWh/year, equivalent to more than 10,000 MW of installed capacity in terms of thermal power plants [32]. There are wide ranges of processes available for converting biomass and wastes into more valuable fuels. These include biological processes to make ethanol or methane, and thermal processes to make heat, gaseous fuels, liquid fuels and solid fuels, The products of gasification vary according to the reactor configuration and oxidant used. Ideally, there is complete conversion of all tars, hydrocarbons and char in the gasifier in to combustible gas [33].

Synthetic gas derives from gasification of biomass such as sugar cane residues [34,35]. It is expected to achieve efficiencies around 40% for atmospheric gasification of wood in biomass integrated gasifier combined cycle. Some modifications would be necessary for the use of this low calorific value fuel in a gas turbine originally designed to use natural gas as fuel. These modifications comprise gas turbine layout for the changed mass flow, fuel delivery/injection system, fuel nozzles, fuel manifold and combustion chamber. Hydrogen available in the biogas has a much higher flame propagation speed than the other components, i.e., CO and CH_4, which gives better flame stability [36].

The syngas obtained from biomass gasification has low heating value. Separate compressors are supposed to compress the gasifier air and this fuel gas for injection into the combustor. Due to the large amount of fuel gas it will requires a considerable quantity of power to be taken from the turbine drive shaft [37]. Fuel-flexible gas turbine operating on alternative fuels such as landfill gas, LNG tail gas, process gas, and synthetic fuels, which is originally designed for natural gas [38].

The fuel delivery nozzle design may be changed to include this gaseous fuel with combination of steam or water for emission control. For this purpose, dual inner circuits for natural gas for starting purpose and for syngas to the combustor. This combustor system effectively burns the low calorific value syngas [39].

Circulating fluidized bed (CFB) gasification of biomass is characterized by acceptance of a wide variety of biomass feeds, flexibility of scale-up from small to large capacity and high quality gas, in terms of particulate levels in the producer gas, and overall emissions reduction. This system gives high gas yield and high heating value of producer gas, and also making the overall system compact [40]. Fluidized bed gasifiers have the ability to handle a wide range of biomass fuels with minimal preprocessing [41].

An inverted cyclone gasifier is a new concept to efficiently gasify biomass waste for use in small-scale cogeneration plants.

The use of cyclone gasifier over the traditional fluidized bed gasifiers is preferred due to its robustness, simplicity and non requirement of separate complex hot gas clean up system. The cyclone gasifier achieves good ash separation and removes significant quantities of alkalis. The cyclone combustor produces a stable flow, with good mixing and burnout rates, and uniform exit conditions. It could be operated in a lean mode to minimize NO_x, with removal of particles above 5 μm to minimize damage to the turbine [42].

The combustion of low calorific value (LCV) gas uses turbulent combustion. The heating value of the gas is in the range of 2.5–4 MJ/m^3 and the pressure may be in the range of 3–8 bar. It gives good combustion efficiency in the gas turbine [43].

Gaseous fuels generated by biomass gasification have widely different properties depending up on changes in feedstock composition. Premix combustion has an advantage for emissions, flame position and stability, but few complications such as flame flashback, auto ignition, and lean blowout are to be handled properly [44]. Instability phenomenon also occurs in lean, premixed combustion, which may lead to high pressure fluctuations, flame extinction, and CO emissions [45].

Integrating gasifiers with gas turbines achieve high efficiencies. In the recuperative gas turbine process, heat from the hot turbine exhaust gas is transferred to the colder compressed air in a heat exchanger between the compressor and combustor. Due to the preheating of the air, less fuel will be required and the thermal efficiency will be increased. A precondition for the recuperative heat transfer is that the exhaust gas should be hotter than the compressed air [46].

The biomass-derived gas (BDG) can also be co-fired with the natural gas in the combustion chamber of gas turbines. This can be done by mixing of biomass-derived gas (BDG) and the natural gas with some modification in the fuel supply system [47]. Very stringent conditions at the turbine entrance should be met in order to minimize erosion, corrosion and deposition. Erosion is mainly caused by particles and the reported tolerances prescribe maximum concentrations between 2 and 200 mg/m^3 [4].

The air supply to the gasifier could be provided either independently, or through a bleed from the compressed air loop. This choice would require extensive compressor modifications and impose control problems on the system. Thus a separate additional compressor is required. In steam-injection cycles, steam is mixed with the compressed air in the gas turbine cycle. Steam is injected at the combustion chamber and at points before entry to the gas turbine. This increases the gas turbine power output [33].

Lean, premixed, pre-vaporized (LPP) combustion constitutes a very promising means for NO_x emissions reduction from gas turbine engines, since air humidification by steam injection results in additional power, provided by the increased mass flow of steam and the enhanced thermal capacity of the mixture, with improved efficiency, since no additional compression work is required. Steam addition to the combustion air is also beneficial to the reduction of NO_x emissions from gas turbines, operating both in the premixed and non-premixed modes. This is mainly associated with a reduction in flame temperature. NO_x levels in premixed methane–air flames were reduced by steam addition even when the peak flame temperature was kept constant. It is mainly due to the fact that the burning velocities decrease significantly with the addition of even small amounts of humidity [48].

Integration of the evaporative gas turbine cycle with gasification of biomass is an interesting technology that may be able to meet emission demands of the future. In a gas turbine cycle, water is evaporated in the compressed air stream. This additional moisture increases the mass flow and reduces the work required for the compressor. So it increases the gross power output and thermal efficiency [49].

9. Pyrolysis

Pyrolysis is the most important process among the thermal conversion processes of biomass. It is an emerging technology, in which biomass is converted to liquids, gases and char, liquid fuels being the main target. Pyrolytic oils, for the combined cycle gas turbine is a good option for power generation [32].

Pyrolysis oils are produced through vacuum pyrolysis of wood waste or softwood. The oil produced has a dynamic viscosity of 18–25 cSt, similar to that for fuel oil. The high viscosity of pure pyrolysis oils creates problems at injection. Viscosity can be reduced by heating just prior to injection but temperature should not exceed 90 °C to avoid chemical breakdown. Viscosity can also be reduced by blending it with alcohol. The combustor performance with mixtures of 80% pyrolysis oil and 20% ethanol is similar to the combustion performance with JP-4. This fuel has reasonable heat of combustion, low sulfur, nitrogen and ash content [50]. The heating value of pyrolysis oil is about 59% of diesel fuel but its cost is quite low so the equivalent energy cost is still lower. The major concern with pyrolysis fuel is the levels of contaminants, i.e., alkali, ash, char and tar. This can be addressed with an external combustor in stationary turbines but for aero-derivative gas turbines it will create problem. The combination of high viscosity, low heat content and low volatility requires the use of a separate starting and shutdown fuel [11].

The pulp process in the pulping industry generates black liquor as a by-product. The black liquor energy content is sufficient to cover pulp mill's steam demand. The combustion chamber has to be modified to restrict emissions, assure flame stability, and allow operation flexibility (e.g., operation with conventional fuel for start-up and back-up purposes) [51].

Power produced from biomass has been assessed as one of the leading candidates for reducing CO_2 emissions in power production. Fast pyrolysis is a potential candidate for power production. Up to about 65% organic liquid fuel from dry low-ash biomass can be produced. Advantages of using pyrolysis liquids as fuel are [52]

- Pyrolysis liquid is the lowest cost liquid bio-fuel, and its CO_2-balance is clearly positive.
- Possibility of utilization in small-scale power generation systems as well as use in large power stations (co-firing).
- Storability and transportability of liquid fuels.
- High-energy density compared to atmospheric biomass gasification fuel gases.
- Potential of using pyrolysis liquid in existing power plants.

The generation of energy by direct combustion of wood in a boiler has a maximum efficiency of 26%. A more efficient way to produce energy can be achieved by burning the bio-oils generated by the pyrolysis of biomass instead of burning the wood directly. The pyrolysis oil has a lower heating value than petroleum fuels and will therefore require an increased fuel flow, which could lead to some modifications in the combustor, particularly in the nozzle. The net heating value of the raw pyrolysis oil is lower than that of petroleum fuels (42 MJ/kg). The addition of methanol slightly reduces the heating value of the pyrolysis oil, but it also reduces the viscosity and the density and increases the stability, which are considerable benefits. A limitation with methanol however, is its low-ash point in the blend. The ash present in fuels, partly in the form of alkali metal oxides, is responsible for gas turbine deterioration [53].

10. Dimethyl ether (DME)

Dimethyl ether (CH_3OCH_3), also known as wood ether or DME. It can be made from natural gas, coal, or biomass. It is much less toxic than the methanol [39]. DME has the same empirical formula

as ethanol (C_2H_6O), but its structure is different, the normal boiling point of DME is −23 °C not much different from that of propane (−42 °C). Hence, DME to be stored in compressed tanks, and the energy density of DME is about 61% that of propane [54]. Conversion of DME is primarily by converting natural gas, coal or biomass such as wood chip via gasification with oxygen and steam to synthesis gas (syngas). Synthesis gas is then converted into methanol in the presence of catalyst (copper-based), with subsequent methanol dehydration in the presence of a different catalyst (e.g., silica–alumina) resulting in the production of DME.

DME is a gaseous fuel and its total efficiency of biomass-to-DME is about 38% [10]. Dimethyl ether (DME) is the simplest ether compound and it is non-toxic and environmental friendly. It has a high cetane number of approximately 55–60, the chemical structure of DME with its high oxygen content promises a smoke-free combustion. It is a relatively new alternative fuel and its properties are quite different from those of diesel fuel. DME has high vapor pressure and low boiling temperature; it is a gas fuel at room temperature and atmospheric pressure. Its handling characteristics are very similar to LPG. The heat value of DME is significantly lower than conventional diesel fuel. Therefore, the fuel supply system, injection system and the combustion system of the gas turbine, to be redesigned or modified. The combustion duration is shorter than that of diesel. The high vapor pressure, low boiling temperature and the high oxygen content of DME lead to rapid fuel evaporation, good fuel/air mixture formation and prompt combustion. The DME exhibits a substantial reduction in NO_x and HC emissions and gives a smoke-free combustion, while CO emission increases slightly in comparison with diesel. So it can achieve high thermal efficiency and low emissions. It will play a significant role in meeting the energy demand while minimizing environmental impact [54].

The simplicity of this short carbon chain compound leads to very low emissions of particulate matter, NO_x, CO during combustion. For these reasons as well as being sulfur-free, dimethyl ether meets the most stringent emission regulations. So DME is a good alternative fuel for transportation and power generation. Most of the results of the combustion performance tests show that DME is very clean and efficient fuel for gas turbines. However, other results have shown that it is necessary to modify the fuel nozzle to the combustor in consideration of the combustion properties of DME to enhance reliability of DME fired gas turbines [55,56].

DME has high potential for commercialization in the coming year. It is convenient to store and transport, since its boiling point is higher than that of LNG (liquefied natural gas). It generates a lesser amount of toxic exhaust gases because there is no carbon to carbon bond in DME molecular, which means that it does not tend to form soot particle, and it is an adjustable fuel for a lean, premixed, pre-vaporized gas turbine, its physical and chemical properties are similar to those of LPG (liquefied petroleum gas) [55,56].

The results of the performance tests show that DME combustion is very clean but hard to control. The CO emission level of DME is lower than that of methane, while the NO_x emission level of DME is as low as that of methane. DME is a very good fuel for power generation with low combustion instability. Retrofit/modification of combustor, fuel nozzle and burner are necessary to use DME as a gas turbines fuel [55].

11. Hydrogen

Hydrogen can be produced via gasification of biomass followed by reforming of the syngas. In the steam-reforming reaction, steam reacts with natural gas to produce CO and H_2, commonly called synthesis gas., Steam at high temperatures (975–1375 K) is mixed with CH_4 gas in a reactor with a Ni-based catalyst at 3–25 bar pressure to yield CO, H_2 and CO_2. In the second stage CO further reacts with steam and produces CO_2 and H_2 from this mixture CO_2 is separated to get hydrogen. Steam reforming of natural gas is currently the least expensive method of producing H_2 [1].

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = +251\ \text{kJ/mol}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -42\ \text{kJ/mol}$$

Hydrogen can also be produced from renewable sources such as gasification of biomass, solar insolation and biological organism, oil oxidation, electrolysis, etc. H_2 production from carbonaceous solid wastes requires two steps catalytic reaction. In the first step biomass is converting into syngas through gasification. In the second stage steam reforming of this syngas is converting it into mixture of CO_2 and H_2. Then pure hydrogen can be separated from the mixture.

Electrolysis is comparatively new and good method for H_2 production. It is having almost 100% conversion efficiency. The electric power source can be diversified; generated not only from the hydrogen gas turbine itself but also from solar, hydraulic, geothermal, wind, etc. The oxygen produced at the same time can greatly contribute to reduce NO_x in burning and to improve the turbine efficiency [57].

The hydrogen fuel is considered to be the easiest energy source for the utilization. Hydrogen has the advantage of zero pollutant emission with the exception of the oxides of nitrogen when burning in air breathing gas turbines. Gas turbine, designed for liquid fuels, can be modified to run on gaseous hydrogen fuel [58]. A hydrogen energy system seems to be a powerful candidate for the alternative energy system. Hydrogen combustion has no hazardous emission like CO_2, SO_x, CO, HC, etc., but thermal NO_x is formed due to the intake air. It is possible to remarkably reduce the thermal NO_x by increasing oxygen content and reducing air content, which surely holds in electrolysis. The combustion dimensions for hydrogen gas turbines can be made smaller sized because the burning speed of hydrogen is much higher than that of conventional fuels like methane (CH_4), propane (C_3H_8), etc. Finally, the combustion temperature of hydrogen reaches approximately 2300 K which is so much higher than that of conventional fuels. Hydrogen is the best fuel from the viewpoint of thermodynamics. So the hydrogen is combustible with higher burning velocity and very diffusive so well mixed with the air thus, the combustion efficiency can reach up to 100% [59].

Hydrogen fuel supply system has to be designed to avoid the explosive ignition, particularly to ensure ignition at a given air–hydrogen mixture ratio. The combustion results of the swirl type fuel nozzle seem to be best. The digital electronic controller is essential to modulate the electrical valve as function of engine speed. Driving the engine with hydrogen, the kerosene is led into the external pot [58].

Hydrogen is a very high-energy density element that holds much promise as a potential fuel for industrial and aircraft gas turbines. The energy density of hydrogen, which is around 120 MJ/kg, is more than double that of most conventional fuels. The main issue with using hydrogen in aircraft engines is its very low density. Even in its liquid state the volumetric energy density of hydrogen is less then half that of other fuels. Storing a sufficient amount of it for use in most applications requires a large volume. Therefore, the use of small quantities like additional fuel could make feasible their use in gas turbine [59]. It will also be useful to reduce polluting exhaust emissions, since the injected hydrogen is in gaseous phase and premixed with the primary air, the primary zone of combustion chamber become more homogeneous and in this conditions CO emission reduces. Addition of small quantities

of hydrogen, substantially reduce the emissions of CO_2 by substitution effect [59].

Integrated gasification combined cycle (IGCC) has emerged as a technology with the potential to reduce emissions of NO_x, SO_x and carbon dioxide to a negligible level. IGCC technology can also be used for the chemical production of hydrogen, ethanol, methanol, and DME (Dimethyl Ether), synthetic gas composed of hydrogen and carbon monoxide. The combustion characteristics of syngas may vary with respect to the ratio of hydrogen to carbon monoxide. A fuel with a high hydrogen content emits more NO_x Synthetic gas does not generate combustion pulsation, unlike methane [59].

One possibility to reduce CO_2 emissions from power production with fossil fuels is to convert the fuels to gas mixtures consisting mainly of hydrogen and carbon dioxide, and to separate CO_2 from the fuel prior to combustion in a gas turbine process. This requires modifications in the gas turbine combustor for H_2-rich fuels. The relatively high adiabatic temperatures of H_2/air mixtures might cause large amounts of thermal NO_x in the flame. The flame temperature, and therefore NO_x emissions, can be reduced by dilution with nitrogen or steam, which lowers the efficiency of the process [60]. NO_x emission depended strongly on the equivalence ratio and swirl. Swirl was effective in reducing NO_x emission [61].

Hydrogen may burned under aircraft gas turbine conditions with minimum possible NO_x emissions while the risk of flash back will be eliminated. So a micro-mix combustor configuration is developed which enables NO_x emissions reduction. Lean burning reactors, if operated well stirred, emit less oxides of nitrogen than those burning with poor mixing quality. For hydrogen combustion premixing would be very desirable from the low-NO_x point of view. However, due to the high reactivity of hydrogen–air mixtures, the risk of flashback and premature burning is considerably higher. The micro-mix combustion may be characterized as an attempt to minimize the scale of mixing and to maximize the mixing intensity. There will burn thousands of small diffusion flamelets instead of 10–100 flames in conventional combustor designs. Safe hydrogen metering and engine control under these conditions is possible. A substantial reduction of the engine's NO_x emissions by application of the micro-mix diffusive combustion of hydrogen could be achieved. So, the diffusive burning will be safe against flash back and reducing the risk of engine failure [62].

Pure hydrogen is a most likely long-term alternative fuel because of its zero carbon emissions and low polluting character. The hydrogen has mainly two hazards, its small molecular size, and its minimum ignition energy. The small molecular size means that hydrogen will easily diffuse out of a system which is completely leak tight to other gases. Its minimum ignition energy makes the hydrogen far more sensitive to ignition than any other gaseous fuel. It also has a much higher flame speed than any other gas; it has wider flammable limits, and also detonates readily [28].

12. Comparison of liquid fuel characteristics

1. Low heating values of liquid fuels

   The low heating values of pure methyl esters (ME) are between 37,500 and 44,500 kJ/kg and are nearly equivalent to LHV of domestic fuel oil. Methanol and flash pyrolysis oil have the lowest LHV.

Table 1
Liquid bio-fuels characteristics.

Properties	Diesel [28]	JET-A [19,50,52]	Straight vegetable oils [9,15,63]	Bio-diesel [11,15–17, 19,22,26,27]	Bio-ethanol [3,27,50]	Bio-methanol	Pyrolysis oil [3,11,50,52]
Density (kg/m^3)	827.4	807	900–940	860–900	794–810	796	984–1250
Kinetic viscosity (cSt at 40 °C)	1.7283	0.88	30–40	3.5–5	1.4–1.7	1.4–1.7	32–45
Flash point (°C)	44	38	230–280	120–180	13	11	56–130
Cloud point (°C)	−6	–	−4 to 12	−3 to −12	–	–	–
Pour point (°C)	−16	−47	−12 to 10	−15 to 5	−117	−161	−35 to −10
Lower calorific value (MJ/kg)	43	43.23	38–39	39–41	25–26	20	13–18
Ignition temperature	250	220	325–370	177	423	463	580
Cetane no.	45–55	55	37–42	48–60	8	5	10
Stoichiometric air/fuel ratio	14.6	14	13.8	13.8	9.79	6:1	34:1
Carbon (%, w/w)	80.33	80–83	76.11	77–81	52.2	37.5	32–48
H_2 (%, w/w)	14	10–14	–	12	13.1	12.6	7–8.5
N_2 (%, w/w)	1.76	–	0	0.03	–	–	<0.4
O_2 (%, w/w)	1.19	–	11	9–11	34.8	49.9	44–60
Sulfur (%, w/w)	<0.4	<0.4	0	<0.03	–	–	<0.05

Table 2
Gaseous bio-fuels characteristics.

Properties	Methane [55,64]	Propane [55]	Syngas [1,5,33,36,44,61]	DME [54,55]	Hydrogen [44,64]
Chemical formula	CH_4	C_3H_8	$CH_{2.68}O_{1.26}$	CH_3OCH_3	H_2
Density (kg/m^3) at 15 °C	717	490	765–785	670	70.8
Boiling point (°C)	−161	−42	−192	−25	−252.8
Vapor pressure at 0 °C (bar)	246	9.3	–	6.1	–
Flammable limits % in air	5–15	2.1–9.4	5–32	3.4–17	4–75
Ignition temperature (°C)	537	470	–	235	500
Max. burning velocity (cm/s)	37	43	–	50	289
Stoichiometric air/fuel ratio	16.9	15.7	9.1	9.0	34.1
Lower calorific value (MJ/kg)	49	46.3	10–18	28.8	120
Cetane no.	0	5	70	55–60	–
Carbon (%, w/w)	75	82	21.8	52.2	–
N_2 (%, w/w)	–	–	1–3	0	–
O_2 (%, w/w)	–	–	73	34.8	–
H_2 (%, w/w)	25	18	4.87	13	100
Sulfur (%, w/w)	–	–	–	–	–

2. Viscosities of liquid fuels

   The viscosities of ethanol, methanol, are lower than the viscosity of diesel oil. These low viscosities allow spraying the fuels more easily. Unlike the other fuels, the vegetable oils and the flash pyrolysis oil have a very high viscosity which can pose a problem to spray the oils in the combustion chamber of gas turbines; however, these fuels may be heated up to decrease their viscosity.
3. Densities of liquid fuels

   The densities of most of the liquid fuels are ranging between 690 and 916 kg/m^3, close to the density of diesel oil (equal to 830–860 kg/m^3). The flash pyrolysis oil has a higher density (equal to 1200–1240 kg/m^3) compared to those of the other fuels.
4. Molar weight of liquid fuels

   The molar weights of hydrocarbon fuels are much lower than bio-fuels. This property also influences the vaporization behavior of liquid fuels, where heavier fuels have lower vaporization rates. However, vaporization rates tend to similar values under high temperature conditions.
5. C/H ratio (w/w) of liquid fuels

   The high C/H ratio (high carbon content) of the flash pyrolysis oil from wood, the vegetable oils and the methyl esters may pose a problem of deposits in the combustion chamber of gas turbines [6] (Tables 1 and 2).

13. Conclusion

A gas turbine is a steady flow engine; it is usually burning diesel or natural gas by using diffusion flame technology with relatively high level of NO_x and partially unburned emissions. The gas turbine develops steady flame during stationary operation. This favorable feature gives a wide range to the different alternative fuels such as natural gas, vegetable oils, esters, alcohols, synthetic liquid and gaseous fuels from biomass, hydrogen, etc.

Based on the properties and availability, the different bio-fuels can be used in the gas turbine for power generation. Non-edible oils and its bio-diesel such as Jatropha and Karanj oils using as pure or blended in diesel can be important alternatives under Indian perspectives.

In lean, premixed, pre-vaporized (LPP) combustion, liquid bio-fuels, such as bio-diesel and ethanol converts into a gas. This LPP gas burns with low emissions and provides substantial fuel flexibility. This gives a clean and reliable use of liquid bio-fuels to make them a primary source for power generation. It constitutes a very promising means for NO_x emissions reduction from gas turbine engines

For conversion of biomass in to more clean fuels, there is a wide range of processes available. These include biological processes to make ethanol or methane, and thermal processes to make gaseous fuels, liquid fuels such as syngas, methanol or hydrogen. The products of gasification vary according to the reactor configuration and oxidant used. Fast pyrolysis is a potential candidate for power production. Up to about 65% organic liquid fuel from dry low-ash biomass can be produced. Pyrolysis liquid is the lowest cost liquid bio-fuel and it is having transportability benefits.

DME is a good alternative, very clean and efficient fuel for transportation and power generation in gas turbines. It is necessary to modify the fuel nozzle to the combustor to enhance reliability of DME fired gas turbines.

Pure hydrogen is a most likely long-term alternative fuel because of its zero carbon emissions and low polluting character. It may burns in gas turbine with minimum possible NO_x emissions while the risk of flash back may be eliminated. It may be possible by the application of the micro-mix diffusive combustion. So, the diffusive burning is safe against flash back and reduces the risk of engine failure.

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